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SHORELINE EVOLUTION OF THE HOLLAND COAST ON A DECADAL SCALE

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ABSTRACT

The decadal evolution of the dunefoot position along 120 km of the Holland coast is analysed. Firstly, a new definition of dunefoot is introduced based on hydrodynamic and morphologic considerations, which is not affected by local and instantaneous processes occurring immediately before the bathymetric survey. The dunefoot evolution over decadal scales indicates the existence of spatial and temporal oscillations in the shoreline position with magnitudes of 2–3 km length and a periodicity of 4–15 years. Two main controlling factors of this behaviour are identified: (1) influence of sub-aqueous bar systems, and (2) changes in the storm-wave conditions reaching the coast. Although the precise controlling processes of the relation between the dunefoot and the subaqueous profile still remain unclarified, we introduce the concept that the development of a morphological bar cycle requires a fixed amount of time-integrated forcing that is proportional to the cumulative effect of storm waves.

Beach mobility along the Holland coast on decadal scales (10–20 m) is similar or lower than mobility introduced by storms or by seasonal cycles. However, it is important to consider these changes for the possible implications on the local vulnerability of the coast to extreme events. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: dunefoot position; decadal evolution; bar systems; cumulative storm effect

INTRODUCTION

The morphological time-scales of shoreface, surfzone and beach-duneface and their dominant processes are quite different (Stive and De Vriend, 1995). In spite of their different morphological time-scales, the control of the shoreface profile on the beach and dune evolution has been described in many coastal areas (Robinson, 1980; Carter *et al.*, 1982; Psuty, 1986; Davidson-Arnott, 1988). During storms and associated surge levels, rapid erosion of the dune takes place. The dune slope becomes steeper and the eroded sediment is deposited on the beach and the shoreface, developing a more weakly sloped and wider beach. After the storm, the sediment of the beachface remains exposed to aeolian processes and tends to be transported onshore. This exchange of sediment occurs without gains and losses of sediment in the case of a stable coast, where the sediment budget is conserved. On an erosional coast, only part of the sand transported offshore from the dune will return after wave-storm conditions. In this situation, the foredune gradually retreats in a landward direction.

Whereas short-term erosion is related to extreme wave events, losses of dune material at larger time scales (some years) are generally due to a net positive, longshore transport gradient, or to a net cross-shore transport pattern (Steetzel, 1993). Typical values of beach and dune erosion for the Dutch coast are about 400 m^3/m (*c.*70 m retreat of the dunes) during strong storm surges and up to 50 m^3/m per year (*c.*2 m/year of shoreline retreat) for the long-term, gradual erosion (Van de Graaff, 1986).

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Recent studies along the Dutch coast have shown interesting aspects of short- and medium-term (from weeks to decades) morphological behaviour of the subaqueous profile (cf. Wijnberg and Terwindt, 1995). Relations between outer and middle bars and the characteristic 'life-cycle' of bar features have been investigated (Ruessink and Kroon, 1994; Wijnberg, 1995). Less well understood are relations between the inner and swash bars and the subaqueous part of the profile (Wolf, 1997). Here an attempt is made to study the joint evolution of the subaqueous (shoreface and surfzone) and subaerial (beach and dune) profile with reference to hydraulic forcing agents. The final objective is the possible definition of relationships that could be applied for the evaluation of the long-term evolution in the context of coastal zone management practices.

Dune erosion observations along the Holland coast during storms reveal that the erosion rate is non-uniform along the beach. The location of the maximum and minimum erosion areas is expected to be strongly influenced by the subaqueous morphology of the littoral profile and, *vice versa*, maximum dune erosion areas are expected to play an important role in the generation of new bar systems.

The objective of this study is to morphometrically characterize the dune evolution along the Holland coast, from Den Helder to Hoek van Holland, and to relate this to the evolution of the entire littoral profile using a long-term morphological data-set (1964–1992). The analysis is complementary to the work carried out by Wijnberg and Terwindt (1995), in which relationships between the morphometric parameters of the subaqueous profile were analysed. First, the possible existence of a longshore rhythmicity in the dune position and its temporal evolution are investigated. Second, this information is compared to the evolution of the subaqueous profile, especially focusing on changes in slope of the shoreface and the behaviour of bar and trough systems. Main parameters considered are the position of the dunefoot, the slope of the duneface, the slope of the beachface (from -1 to $+1$ m NAP contour), and the position of the 4 and 5 m depth contours.

STUDY AREA

The Netherlands coast may be subdivided into three coastal subsystems: (1) the estuarine Zeeland area in the south, (2) the central part or the Holland coast and (3) the Frisian barrier islands in the north (Figure 1). This work is focused on the Holland coast which is characterized by an almost uninterrupted dune row and without barrier islands and tidal inlets. It is a slightly curved coast running SSW–NNE over a distance of almost 120 km from the entrance of Rotterdam harbour near Hoek van Holland in the south to the port of Den Helder in the north (Beets *et al.*, 1992). The main man-made structures along the coast are the Scheveningen and IJmuiden harbours (km 102 and 55·5 respectively), the 4·5 km long sea dyke near Petten (km 21–25) and the dyke of Den Helder (Figure 1).

Four different zones along the Holland coast were examined separately for the present analysis. These zones are based on the five large-scale coastal behaviour regions defined by Wijnberg and Terwindt (1995), but the northern zone (km 3–8), influenced by the ebb tidal delta evolution, and areas close to harbours and the Hondsbossche dyke were excluded from the analysis since their evolution is strongly affected by man-made structures at all evolutionary scales. These four zones are (Figure 1): (1) km 8–20, (2) km 28–52, (3) km 63–95 and (4) km 104–114. Boundaries between these are the Hondsbossche dyke (km 23), and the IJmuiden (km 55) and Scheveningen (km 102) harbours. The northern and southern zones are periodically affected by beach nourishment, and groin fields influence both. In contrast, in both central zones virtually no direct human interference by structures or nourishment has taken place.

The typical littoral profile is morphologically characterized by a foredune and two or three longshore bars (Figure 2). Foredunes along the Dutch coast have been globally classified as regressive, stable and progressive based on their evolution during the last decades (Arens and Wiersma, 1994). In the northern part of the Holland coast, regressive and progressive as well as natural and artificial foredunes alternate within a range of several kilometres. In contrast, in the southern part the variation is small and comparable types of foredunes extend over most of the region (Arens and Wiersma, 1994). The width of the dune fields ranges from 500 to 2500 m (Stolk, 1988).

The subaerial beach (from the foot of the vegetated dune to low-tide water) averages 43 m in width and the mean slope is 1:15 (Short, 1991). The shoreface consists of a narrow inner slope (> 1:100) and a wider, lower gradient outer slope (1:100 to 1:1000). The shoreface–shelf boundary is located at 17 m water depth. The

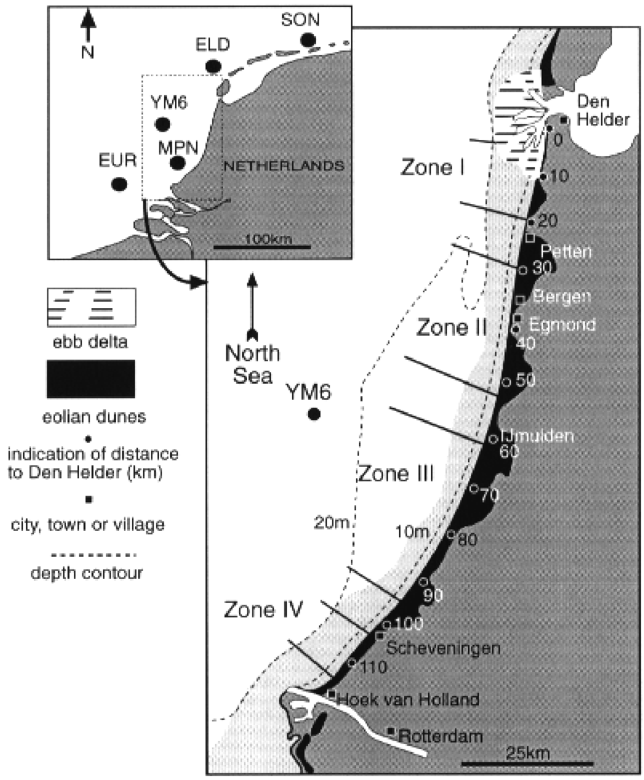

Figure 1. Location of study area and the five offshore wave stations: EUR, Euro-platform; MPN, platform Meetpost Noordwijk; YM6, IJmuiden; ELD, Eierland; SON, Schiermonnikoog. The longshore distances (in km) are measured from Den Helder

width of the entire shoreface zone decreases from about 10 km in the north and south to 2·5 km in the central region (40–85 km) (Short, 1991). The inshore slope gradient (to 8 m depth) is lower (0·01) between km 40 and 90, and increases (0·015) both towards Den Helder (0–40 km) and Hoek van Holland (90–118 km). Lower gradients are typically related to the presence of a three-bar system and the steeper gradient to a two-bar system. It is suggested that the slope regulates the number and spacing of the bars that a particular wave period can generate (Short, 1991). The beach system includes the subaerial beach and surf zone. It consists of (1) a beach-bar usually attached to the beach as a ridge and runnel system, (2) an outer bar, highly rhythmic and rip-dominated, and (3) a longshore bar (Short, 1992).

Main morphological features along the Holland coast are breaker bars (Figure 2). The decadal bar behaviour along this coast has recently been investigated using empirical eigenfunction analysis (Wijnberg, 1995). In that study, the first eigenfunction represents the average profile while the second and third eigenfunction indicate bar morphology and the region of accretion and erosion in the period of analysis. A common characteristic is the presence of a two- or three-bar system with an almost parallel orientation to the shoreline. These bars are cyclic morphological features: they are initiated near the shoreline, migrate while growing initially in the offshore direction and finally decay and disappear in the deeper part of the littoral profile. The disappearance of the outer bar seems to result in the development of a new bar near the shoreline. The return period of consecutive bars across the profile ranges between four and 15 years along the Holland coast (Wijnberg, 1995).

Sediment grain sizes in the dunes are 200–250 μm and 250–300 μm on the beach. In the surf zone sediments are coarsest at 200 m (230 μm), finer seaward between 400 and 800 m (185 μm) and again coarser

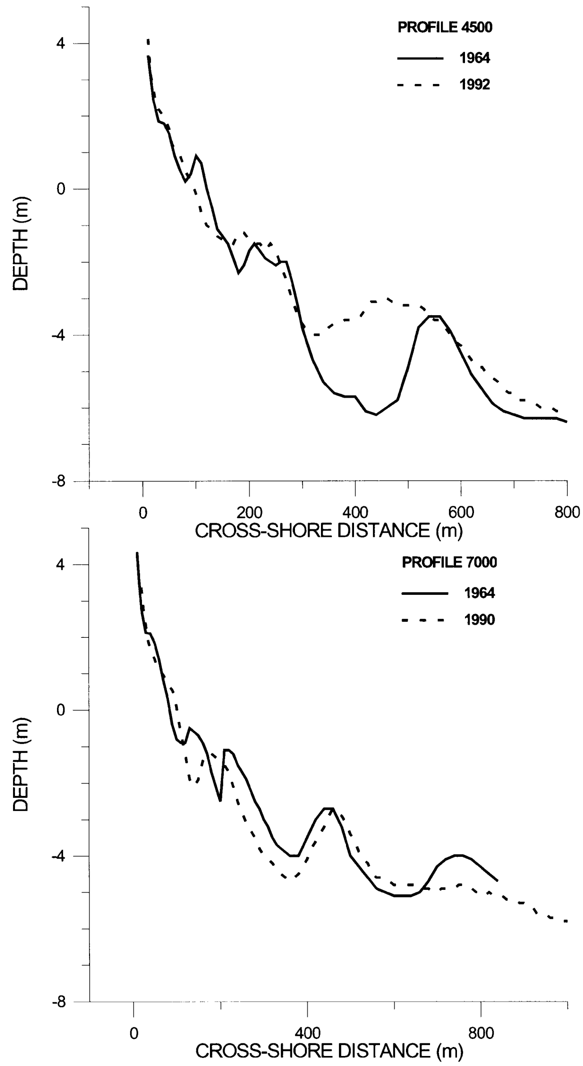

Figure 2. Examples of representative cross-shore profiles located at km 45 (Zone II) and km 70 (Zone III) (see profile location in Figure 1)

between 800 and 1000 m (200 μm) (Short, 1992). At 20 m depth the sediment grain size is 125–250 μm, although between IJmuiden and Scheveningen some zones exist with coarser sediment (250–500 μm) (Stolk, 1988).

The tide ranges from 1·7 m near Scheveningen to 1·4 m near Den Helder. The mean wave height is about 1·2 m and the mean wave period is about 5 s (Roskam, 1988). Waves approach the coast mainly from southwesterly and north-northwesterly directions and alongshore differences in wave climate are small. The wave climate distribution consists of four seasons (Short, 1992): summer (April–August), autumn (September–October), winter (November–January) and spring (February–March).

The influence of the shoreface morphology on the evolution of the beach-dune system along the Holland coast during the last thousand years has been pointed out (Wiersma and van Alphen, 1988). Sand supplied

from the shelf has led to the formation of the Younger Dune Sands between 1000 and 1900 AD and has produced a steepening of the nearshore gradient from 1:200 to 1:100 between 0 and 5 m water depth (Roep, 1984). Differences in the shoreface slope along the Holland coast cause changes in the wave energy reaching the beach and modify the breaker wave heights, which has a potential interaction with the generation of low frequency motions in the nearshore (Short, 1991).

During the 1964–1988 period, coastal erosion was concentrated near Hoek van Holland, Kijkduin and Scheveningen (Dillingh and Stolk, 1989). From Wassenaar to Egmond aan Zee the coast is stable or progrades (up to 1 m/year). Directly to the north and south of IJmuiden progradation occurs (2–4·5 m/year) and 5 km south and north of IJmuiden significant retrogradation occurs locally. The coast is retrograding to the north of Egmond aan Zee. The erosion is more pronounced near Den Helder than it is near Egmond (0·5–1·5 m/year).

Cross-shore transport is held responsible for most of the progradation along the central part of the coast of Holland (Wiersma and van Alphen, 1988; Stive and Eysink, 1989). Erosion in the north is thought to be largely due to loss of sand to the Wadden Sea through the Texel inlet (Stive and Eysink, 1989). This is caused in response to a relative sea level rise of 0·15–0·20 m in the past hundred years (De Ronde, 1982). The present erosion in the south is ascribed to the net northward longshore losses due to wave and tidal motion enhanced by the harbour moles and entrance channels of the ports of Rotterdam and Scheveningen (Stive *et al.*, 1990).

METHODOLOGY

The JARKUS data-set

The medium-term beach and dune evolution for the period 1964 to 1992 was analysed using the JARKUS data-set. This data-set comprises fixed measuring profiles perpendicular to the coastline extending along the Dutch North Sea coast. The distance between profiles is 200–250 m and the total number is about 3000. The subaerial part of the profile was initially gathered by levelling, but since 1977 photogrammetric methods are used (accuracy *c*. 10 cm). The subaqueous part is gathered by sounding (accuracy *c*. 5 cm). Both parts of the profile overlap in the intertidal area and both are referenced to the Dutch vertical ordnance datum (NAP). Along the Holland coast, yearly profiles, approximately from the foredune to 1000 m seaward, are available since 1964. Profiles are usually surveyed between early April and late September and, as a consequence, the profile sampling has a seasonal bias, although it is expected that the biased sampling does not cause a strong bias in the shapes of the profiles (Wijnberg and Terwindt, 1995).

The bar behaviour along the Holland coast can be characterized in a simple way by the distance from the mean dunefoot position in each profile (averaged over the study period) to some fixed depth (between 3 and 6 m). This distance indicates the evolution of the middle bar: the average location of the fixed depth corresponds to the zero position and positive and negative values reflect the bar displacement in offshore and onshore direction respectively. When the crest of the bar becomes deeper than the reference depth because of the offshore migration of the bar, the negative distance reflects the position of the new bar near the shoreline. The employed reference depths have been 5 and 4 m in Zones II and III respectively. Different depths were selected because the seaward limit of JARKUS profiles is shallower in Zone III than in Zone II owing to the gentler slope of the profile. More sophisticated techniques, based for instance on the extraction of the morphometric characteristics, fall outside the scope of the present analysis.

Dunefoot definition

The dunefoot, being a transition point between the beach and the mainland, is, in practice, taken as the position of the waterline or the position of the maximum storm surge level (Van de Graaff, 1990). More objectively, the dunefoot can also be derived from a morphological criterion, where the dunefoot position is defined by the change in slope of the littoral profile, from the steep duneface to the gentler slope of the beachface. None of these definitions is completely useful for our analysis. In our morphometric analysis of the dune and beach system along the Holland coast, a representative dunefoot evolution along the year is

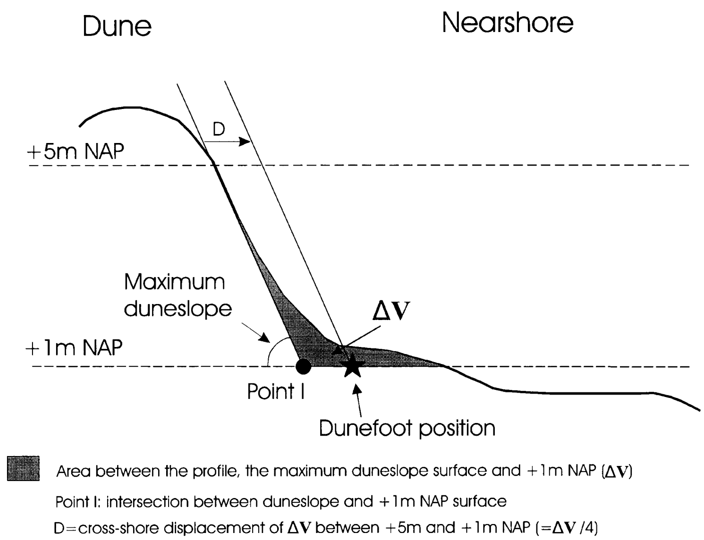

Figure 3. Diagram showing the dunefoot definition used in the study

needed, where morphological changes caused by local and instantaneous processes acting immediately before the survey are not relevant. Moreover, the analysis must be simple because it must be applied to a wide range of profiles with different characteristics. Under these preliminary conditions, an empirical, morphologically defined procedure based on two constant planar surfaces was chosen (Figure 3).

The adopted base level of the dunefoot is the +1 m NAP height, which approximately corresponds to the mean sea high water level along the Holland coast and separates the subaerial and subaqueous parts of the littoral profile. The sediment above this level is only affected by marine transport processes during high-energy (storm) conditions. The definition of the second planar surface or the dune slope is less evident. In our approach, the maximum slope across a horizontal distance of 10 m was calculated in each profile between +1 and +5 m NAP height levels. The characteristic dune slope is defined by the average value of this maximum slope in each zone during the study period (1964–1992).

A theoretical surface with the estimated characteristic dune slope starts at the +5 m NAP point of the real profile and extends down to the intersection with the +1 m NAP surface (point I, Figure 3). The area between the theoretical surface and the real profile is computed and the mass balance is applied to the position of the point I, which is proportionally displaced shoreward or landward. By using this methodology the temporal changes in the calculated dunefoot position indicate changes in the volume of sediment stored in the dune–beach system between +1 and +5 m NAP heights. This allows the comparison between all the profiles in a coherent way.

The choice of the +5 m NAP height as the upper boundary is not completely objective. Our preference is based on the fact that it is the storm-surge design level height for dune erosion in The Netherlands (Vellinga, 1986). The +5 m NAP height storm-surge level has a return period of 10 000 years and was the maximum storm level reached in the flood that affected the Dutch coast in 1953. Therefore, the volume of sediment stored between the +1 and +5 m NAP heights seems an appropriate measure for studying the medium-term evolution of the dune and beach system. The calculated dunefoot migration is not directly related to the total volume change in the dune, which also depends on the dune morphology above the storm-surge level.

The average position of the dunefoot in each profile during the study period was estimated and the dunefoot positions were referenced with respect to this theoretical location. In this way, we can compare the overall profiles with respect to the same relative position.

In order to filter the effects of long-term processes on a decadal scale, differences have been considered between the observed position of the dunefoot in the profile and the linearly detrended position of the dunefoot. We assume that the general evolutive trend of the dunefoot is linear and it is caused by processes acting on longer-term scales, not relevant to our decadal analysis aimed at identifying relationships between the beach and dune system. It is expected that the residuals give information about the decadal and subdecadal behaviour of the dunefoot.

Wave data

Wave data are derived from five offshore stations located along The Netherlands coast (Figure 1). These stations have registered from 1979 to the present, although data from the second half of 1981 are missing. Hydraulic and meteorological data are sampled at intervals of 3 h. During the study period, 1090 'storm events' have been identified (De Valk *et al.*, in press): an event starts when at least one of the three variables (significant wave height, surge level or wind speed) exceeds the value which is exceeded 5 per cent of the time. The 'storm event' continues as long as one variable exceeds the criteria in some station. Two intuitive, dimensional parameters are defined in order to characterize each storm event in relation to the dune evolution:

$$A = (H_{\mathrm{mo}}\, t^{1/2}) \quad [\mathrm{ms}^{1/2}] \quad \text{wave-storm parameter}$$
$$B = (SLt^{1/2}) \quad [\mathrm{ms}^{1/2}] \quad \text{surge-storm parameter}$$

where H_{mo} is the average significant wave height ($= \sqrt{4}M_{\mathrm{not}}$, M_{not} being the zerothorder moment of the frequency spectrum) during one storm event, *SL* is the average instantaneous sea level during the storm event, and *t* is the duration of the storm. The square root of the storm duration was used to account for the fact that the intensity of the dune erosion decays with the duration of the storm (Vellinga, 1986). These parameters were calculated using the data from the YM6 wave-station, which is centrally located in front of IJmuiden harbour and it is assumed as representative for the entire Holland coast. No wind parameter is calculated, although the wind speed data are indirectly considered in the 'storm parameters' because they are included in the definition of 'storm event'.

We adopt the hypothesis that the evolution of the dunefoot position (and the whole nearshore profile) is related to the cumulative effect of storm waves between two successive surveys. Because profiles were surveyed between April and September, the cumulative yearly value of the previously defined wave parameters has been estimated from 1 July to 30 June of next year. This implies that we assume the surveys to have been taken on 1 July of each year, which corresponds to the average of the real time (April to September). In this way, we filter seasonal wave oscillations that are noise in our analysis, and adopt the concept of 'cumulative' parameters rather than 'average' parameters. This is based on the idea that the morphological evolution of the profile is the response to the cumulative storm effects. The use of a cumulative storm parameter was introduced by Bryant (1988) ('seasonal' and 'annual' storm index), who demonstrated that the cumulative storm index has a marked impact on the shoreline position. The cumulative storm parameter allows the beach system to be considered as resulting from the 'integration' of the forcing events with a kind of natural 'discharge' factor occurring during the fairweather periods.

The temporal series of the 'surge-storm' parameter at the YM6 station shows the seasonal wave climate affecting the study area (Figure 4A). A major storm occurred in 1990, but a general trend is not obvious. The normalized curves of both annual cumulative surge-storm-wave parameters, however, show trends, clearly with a similar distribution (Figure 4B): minimum values (or minimum storm energy) occur in the years 1980, 1985–1986 and 1991, whereas maximum storm energy periods are 1982–1984 and 1990. The parameter related to the wave height displays a more complicated distribution showing an intermediate, high-energy peak, during the year 1987 which is missing in the surge level distribution data.

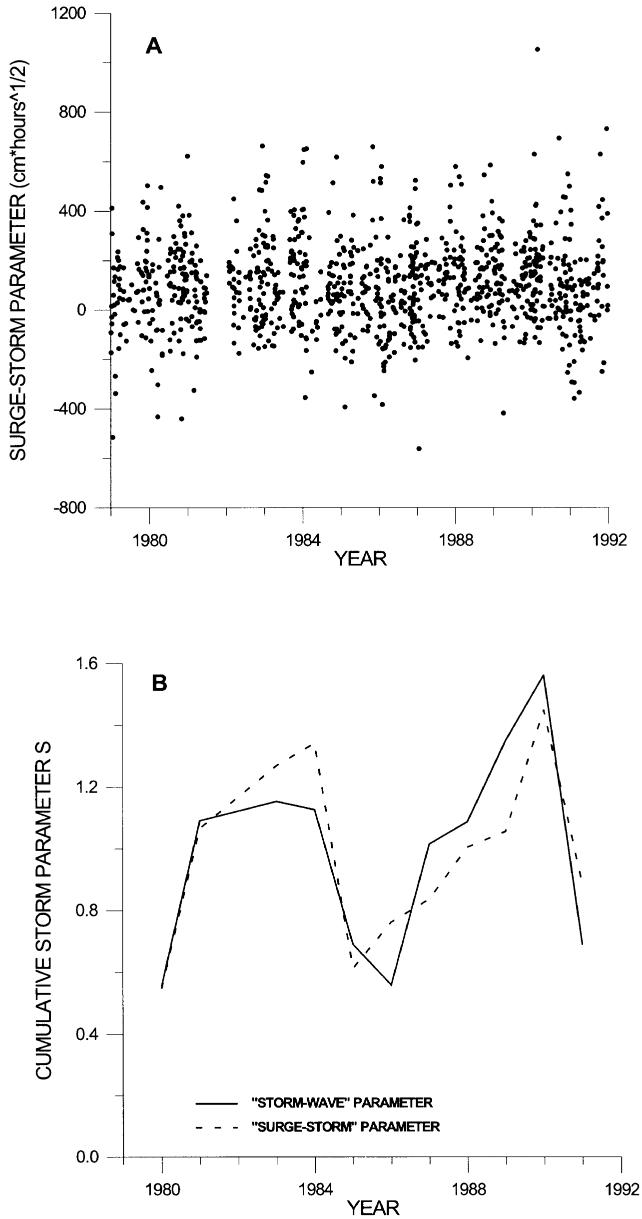

Figure 4. Storm-wave parameters measured at the YM6 station (IJmuiden). (A) Surge-storm parameter; (B) evolution of the annual cumulative storm parameters normalized by the average value of the data-set ('wave-storm' parameter $= H_{m0}\ t^{\frac{1}{2}}$; 'surge-storm' parameter $= SL\ t^{\frac{1}{2}}$)

RESULTS

Spatial variability of the dunefoot position

The average maximum slope of the duneface is rather constant in the four zones analysed (tg $\beta = 0{\cdot}14$–$0{\cdot}15$). The average beachface slope, estimated between +1 m NAP and −1 m NAP, ranges from 0·025 to 0·030 in

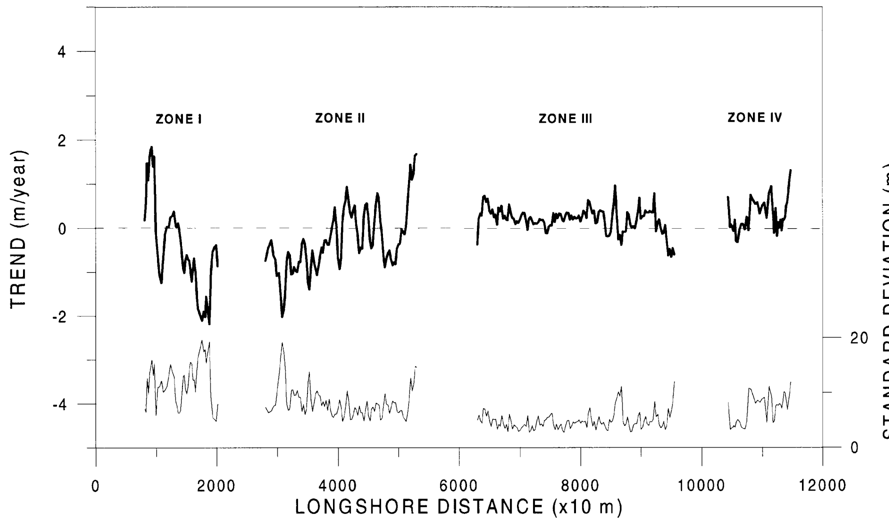

Figure 5. Linear trends and standard deviation of the dunefoot position along the Holland coast during the period 1964–1992

the four zones, implying that the mean beachface width is about 70–80 m along the entire Holland coast. The dunefoot is located at a distance of about 25 m (range 10–50 m) shoreward from the position of the +1 m NAP contour in the profile and it corresponds to a height of +1·7 m NAP in the averaged morphological profile. Mean profile slopes, from the dunefoot to 7 m depth, range between 0·006 and 0·02. The steepest slope occurs in Zone I (0·009–0·02) and the gentlest slope in Zone III (0·006–0·009).

The position of the idealized dunefoot shows high longshore variability with respect to the position of the reference line. The standard deviation of the dunefoot position is always below 20 m (Figure 5). The standard deviation decreases towards the south from average values of 15 m at km 10, to 5 m between km 60 and 90. The trend of the dunefoot migration obtained from linear regression during the study period also indicates high longshore variability, although two main sectors can be differentiated (Figure 5): northward of km 40 erosional trends are dominant, and southward of this location the accretion is dominant. In general, trends are lower than 1 m/year, except in some profiles located close to the harbours.

The correlation between the position of the dunefoot in the profile and of the +1 m NAP, 0 m and 1 m depth in each coastal zone separately examined is in the range 0·90–0·97, 0·77–0·96 and 0·62–0·91 respectively. Figure 6 represents these relations in Zone II. On the other hand, the position of 5 m depth contour shows a poor or no linear correlation with the dunefoot position. In Zone I, the position of the 5 m depth contour is affected by the presence of sedimentary outcrops in the shoreface ('terraces'). In the other zones, the position of the 5 m depth contour in the profile is highly variable and it is an indicator of the position of breaker bars. In general, the standard deviation of the different parameters increases with depth. For instance, the standard deviation of the dunefoot is about 5–10 m, the +1 m NAP contour is 10–20 m and the 1 m depth contour 20–40 m in Zone II. The standard deviation of 5 m depth contour position in this zone is greater than 200 m.

Evolution of the dunefoot

Trends of dunefoot evolution obtained from linear regression during the study period have been presented above (Figure 5), but the observed yearly evolution of the dunefoot is of a more complex character (Figure 7). The dunefoot evolution in Zones I and IV is highly affected by soft and hard measures. Zone I shows a strong retreating gradient from 1964 to 1984/1985, when the dunefoot started to be accretional. The beach nourishment carried out in this zone during years 1986 and 1987, when about 3×10^6 m^3 of sand were

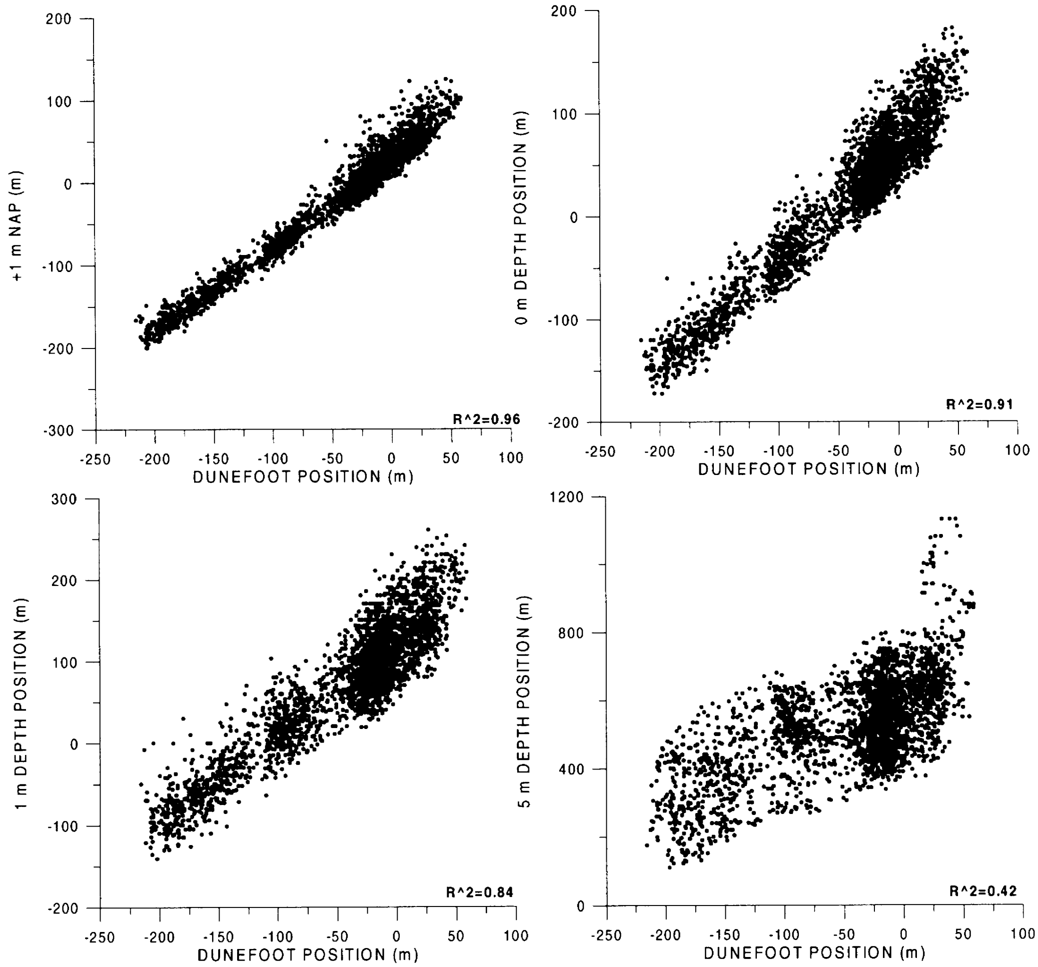

Figure 6. Relationships between dunefoot position and +1 m NAP, and 0, 1 and 5 m water depth in zone II

supplied to the beach, presumably caused the change in this trend. Zone IV shows a slightly accretional dunefoot position during the study period. The average evolution displays the presence of oscillations in the dunefoot position, with 'accretional' periods during years 1964, 1971, 1982 and 1987. The year 1987 represents a major perturbation in the average dunefoot evolution produced by the artificial nourishment of about 3×10^6 m^3 of sand on the beach.

Zones II and III show a general erosional and accretional trend respectively. Superimposed on this general trend, some oscillations in the position of the dunefoot can be observed. These oscillations are unrelated to human intervention and for this reason we will focus here on these 'natural' zones. The dunefoot evolution is significantly different in both zones and they will be described independently.

Zone II (km 28–54). The evolution of the detrended position of the dunefoot exhibits longshore and temporal oscillations north of IJmuiden harbour (Figure 8). In the longshore direction, alternating 'accretional' and 'erosional' positions of 2–3 km extent are observed along the coast. The temporal

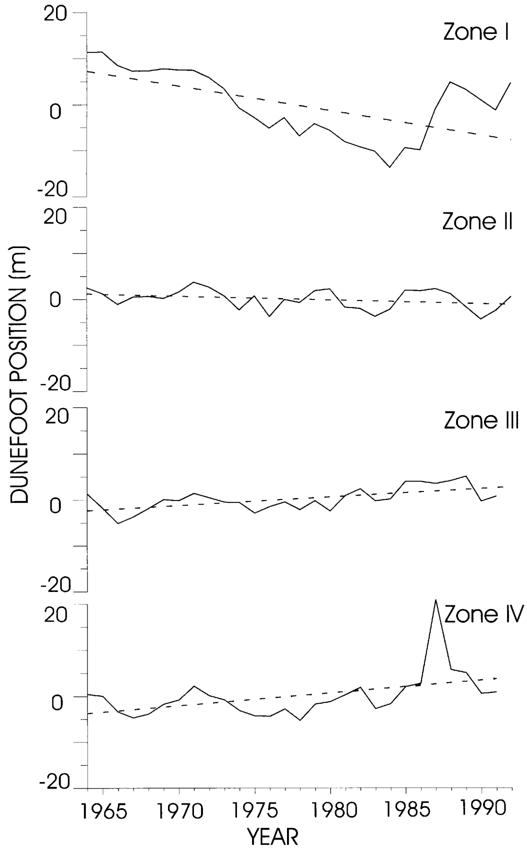

Figure 7. Yearly evolution of the dunefoot position in the four analysed zones showing the general trend estimated from linear regression

evolution of this longshore rhythmicity may be viewed as a shoreline wave propagating towards the south with a propagation speed of 150–200 m/year. The amplitude of the oscillation is about 20 m and its periodicity is about 10–15 years. These 'sand waves' are better developed in certain areas and during specific periods. For instance, during years 1966, 1975, 1983 and 1990 discontinuities in the propagation of sand waves are observed and these trends disappear near the IJmuiden harbour (km 55).

Zone III (km 60–95). The dunefoot evolution south of IJmuiden harbour is very different from that to the north (Figure 8). In Zone III, periods of 'accretion' and 'erosion' alternate nearly simultaneously along the entire coast and no longshore trends are detected. The most general accretional positions occur in years 1964, 1971 and 1987, whereas general erosional positions take place in years 1966, 1979, 1983 and 1990. Oscillations in the position of the dunefoot of more local character can also be observed, especially during the period 1975–1983.

In spite of the important differences in the evolution of the dunefoot position in both zones, inspection of Figure 8 reveals that some positions of 'accretion' and 'erosion' occur simultaneously along the entire coast. This fact is shown in Figure 7, where positions of the dunefoot in both zones are displayed. The 'accretional' positions in years 1964, 1971 and during the 1985–1988 period and, on the other hand, the 'erosional' positions in years 1966, 1983 and 1990 took place simultaneously in both zones. During the period 1975 to 1982 the evolution in both areas appears to be uncorrelated.

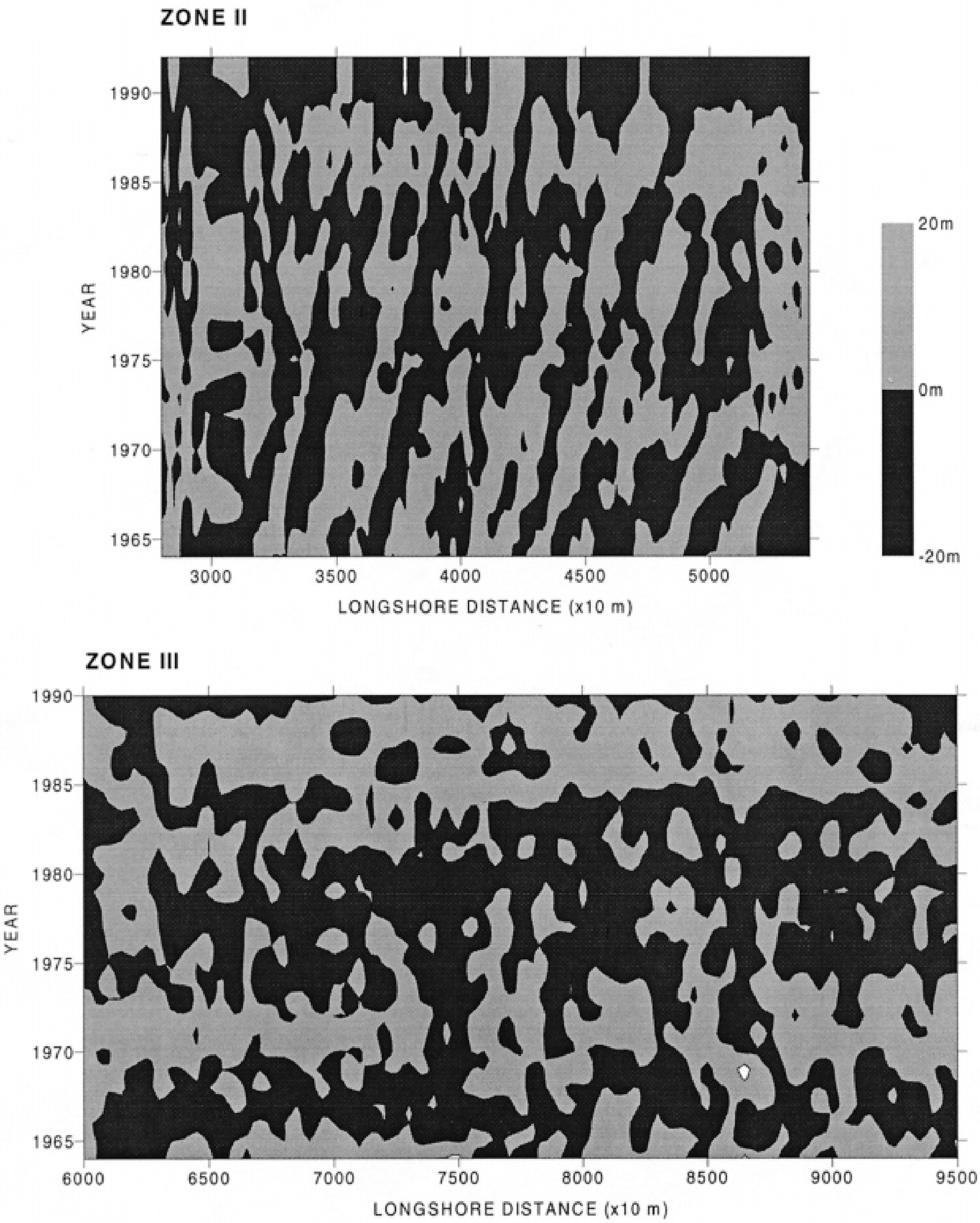

Figure 8. Residual dunefoot position oscillations in Zones II and III; shoreward (dark) and seaward (light). The longshore distances are measured from Den Helder.

Evolution of the nearshore profile

The characteristic bar evolution in Zone II, based on the position of the 5 m depth contour with respect to the dunefoot, is shown in Figure 9. The bar appears to be generated at the shoreline and propagates in an offshore direction until the bar disappears and a new bar appears in the profile. The return period of this repetitive process is approximately 10–15 years and the total cross-shore displacement of the bar system is 400 m. The position of the bar with respect to the dunefoot is not homogeneous along Zone II because of

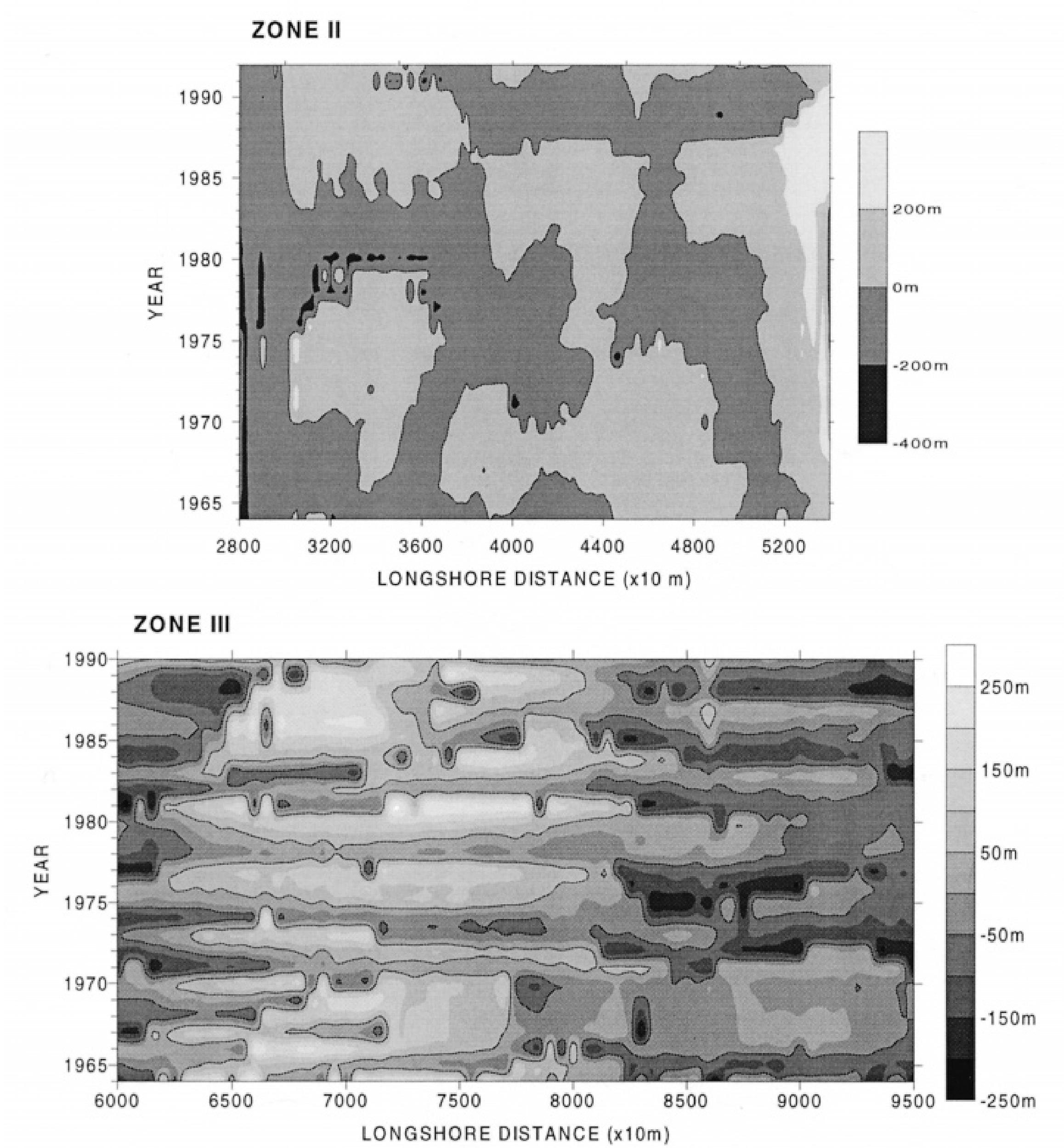

Figure 9. Nearshore bar evolution represented by the position of 5 m depth (Zone II) and 4 m depth (Zone III) with respect to the average dunefoot position. The zero position represents the average location of the considered depth, and positive and negative values indicate an offshore and onshore displacement respectively

longshore discontinuities. Moreover, the bar displacement is not in phase alongshore, representing an obliquity relative to the dunefoot position. The appearance–disappearance of a bar in the profile first occurs in the southern area and it progressively propagates towards the northern area. This disposition can be seen as an oblique bar, with the northern side closer to the shoreline than the southern one. The major discontinuity in

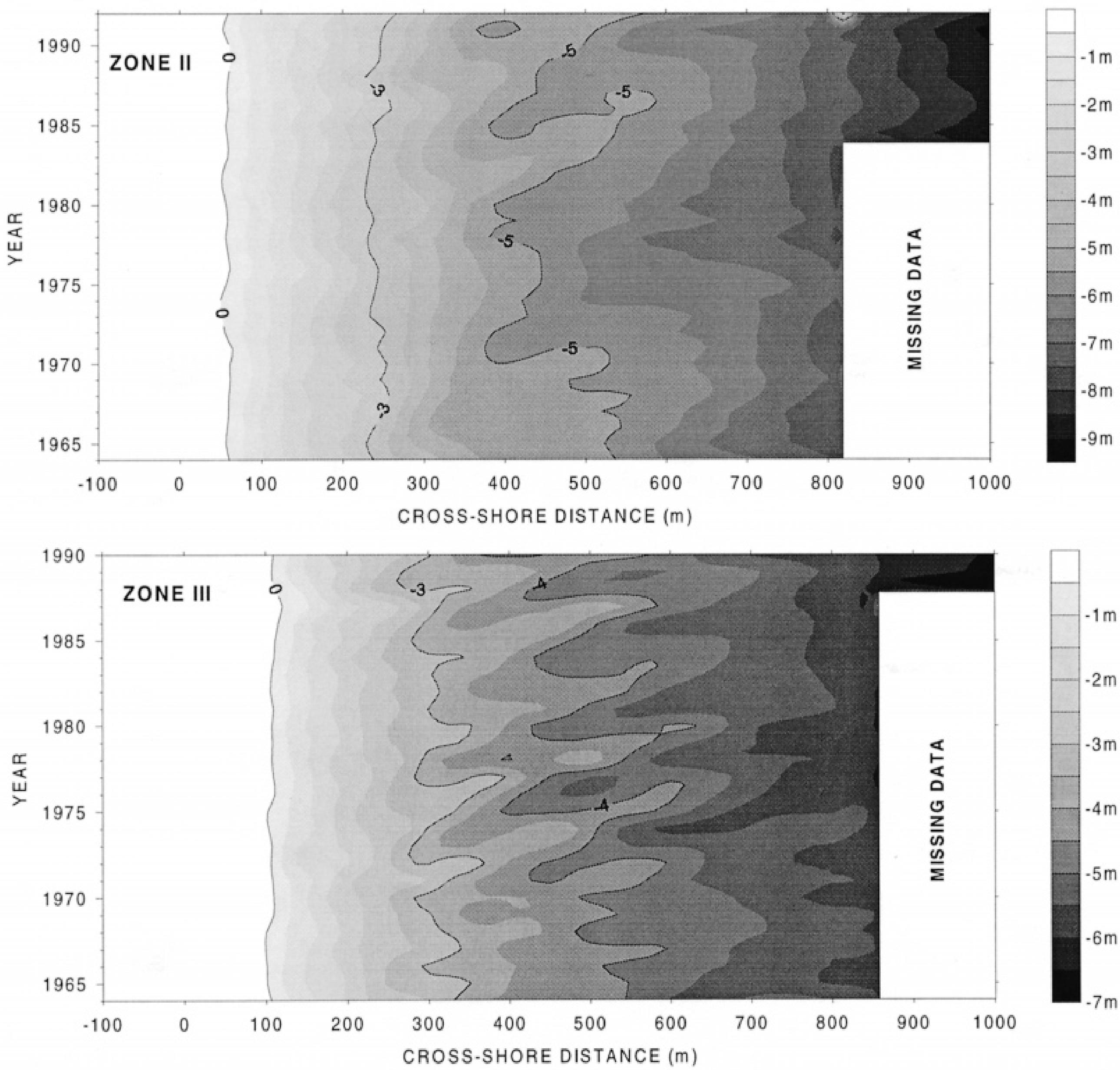

Figure 10. Evolution of the average yearly profiles in Zones II and III showing the different behaviour of the bar systems in both zones

the bar position is located around km 41 in the year 1964 and tends to move towards the south. The southern edge of Zone II is affected by the presence of the IJmuiden harbour, which influences the morphological developments. Minor longshore discontinuities (length about 2–3 km) in bar disposition are mainly caused by the crescentic morphology of bar systems in this zone (Wijnberg, 1995).

The behaviour of bars systems in Zone III is represented by the position of the 4 m depth contour in Figure 9. The evolution shows important differences with respect to Zone II. Firstly, the bar return period is about

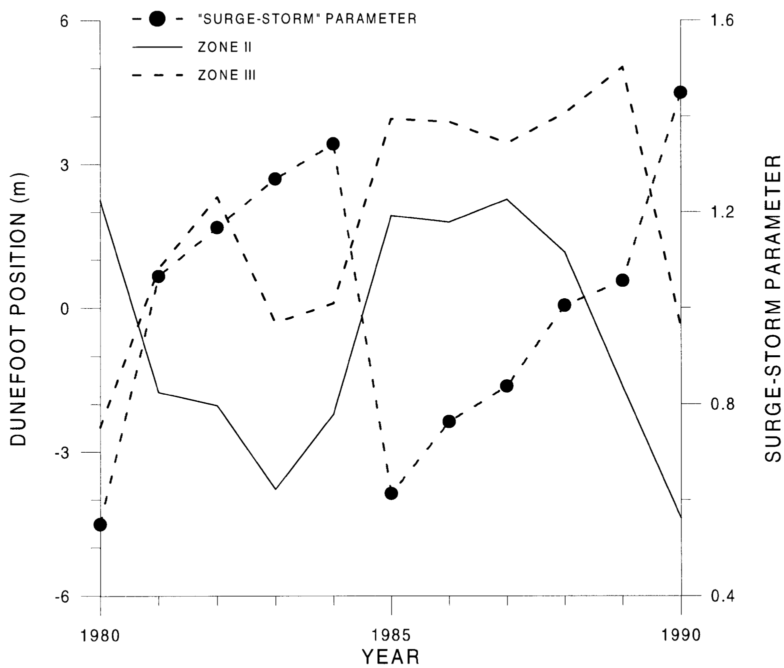

Figure 11. Comparison between the cumulative 'surge-storm' parameter and the yearly averaged dunefoot position in Zones II and III

four years. On the other hand, the relative position of the bar seems to be rather homogeneous along the entire coast and no longshore rhythmicity is observed.

The annual mean profile has been estimated considering the overall profiles in each zone in order to analyse the morphological behaviour of both the profile and bar systems (Figure 10). In Zone II, the evolution of the average profile displays the bar migration in an offshore direction from 1964 to 1978 and from 1978 to 1990. The major disturbance produced by bar migration is located between 3·5 and 7 m depth and the morphological variability decreases in both onshore and offshore directions. The disappearance of bars shows a periodicity of about 13–15 years. In Zone III, the highest mobility area of the profile is located between 3 and 4·5 m depth contours and this variability is caused by the offshore - directed bar migration. The morphological periodicity is about four years (Figure 10).

It should be pointed out that we can observe the general patterns of bar behaviour from the yearly average profile in each study zone. This fact suggests longshore coherence in each study zone, which is observed in the spatial analysis in Zone III, but it was not as evident in Zone II, where discontinuities in bar disposition are observed along the coast (Figure 9).

Comparison between the temporal distribution of the cumulative surge-storm parameter and the evolution of the dunefoot position indeed shows good agreement (Figure 11): years with erosional positions in the dunefoot correspond to maximum cumulative surge-storm energy periods, whereas accretional positions occur during low-energy surge-storm conditions. This relationship suggests that the magnitude of the annual erosion–accretion trend on the shoreline of the Holland coast is closely related to the cumulative effect of storms.

DISCUSSION

Beach mobility, as defined by Dolan *et al.* (1978), is the standard deviation of the mean position of the shoreline. It is a function of the morphodynamic state of the beach (Short and Hesp, 1982): dissipative,

intermediate and reflective beaches correspond to low–moderate, moderate–high and low beach mobility respectively. On Australian beaches, the standard deviation of the shoreline position measured several times every year ranges between 5 and 14 m when temporal data series of one to five years are considered. The shoreline mobility of the Holland coast during the period 1964–1992 (represented by the position of +1 m NAP contour measured yearly) is higher, about 20 m, suggesting that the beach mobility parameter increases when longer time-scales are considered. On the other hand, the mobility of the position of the dunefoot, such as defined in this work, is approximately half that of the mobility of the shoreline, namely about 10 m. We should not forget to consider that the dunes are often vegetated, thus increasing the relative stability. The dunefoot position seems a more appropriate parameter for the study of the shoreline evolution on decadal scales because it partially reduces 'noise' in the variability related to short-term processes (storm impact, seasonal changes or small-scale morphological changes).

The definition of the dunefoot introduced in this study includes both morphological and sediment balance criteria. In our definition, 1 m of cross-shore displacement of the dunefoot represents a sediment volume variation in the subaerial beach of 4 m^3/m, because the considered morphological change ranges between +1 and +5 m height in the littoral profile. Thus, the mean standard deviation of approximately 10 m for the dunefoot position during our study period implies a subdecadal volume variation of 40 m^3/m. This amount of sediment is small when compared to dune erosion caused by extreme storm events on the Holland coast (e.g. local observations show 100–500 m^3/m of sediment eroded and 25–75 m of duneface retreat) (Steetzel, 1993). However, the present method of measuring dunefoot displacement (and associated volume variation) along the Holland coast which averages out extreme events is of the same order of magnitude as volumetric changes in the littoral profile along different coasts around the world when trends over longer periods of time are considered. For instance, data reported by Dubois (1988) in Delaware on the seasonal volumetric exchange of sediment between beach and nearshore zones indicate volumetric variations between 4 and 133 m^3/m. From a more general point of view, an empirical relationship for median erosion in duneface retreat was established using long-term data-sets (> 100 years) (Hallermeier and Rhodes, 1988):

$$\mathrm{Erosion}[\mathrm{m}^2] = 8Rin^{0.4}$$

where *Rin* is the recurrence interval (years) of surge-level conditions. Considering the recurrence interval of interest in our study to be 10 years, the expected duneface erosion would be about 20 m^3/m, which is similar to the volumetric variability observed along the Holland coast.

The analysis of the dunefoot–shoreline evolution along the Holland coast on a decadal scale indicates that the shoreline change is caused by different processes acting simultaneously on the coast but with different time-scales. The 'regional', decadal evolution trend of the shoreline is not considered in the study and it is filtered in a simple way considering a linear trend. This general erosional or accretional trend of the shoreline is related to processes of longer period than the ones analysed in this study (some decades), such as processes controlling the sediment budget on the coast (Stive *et al.*, 1990). On the other hand, high-frequency oscillations in the position of the shoreline, related to a single storm effect or seasonal wave climate changes, are not considered either in the study. This is because of the frequency of data acquisition (annual) and the criteria employed in the definition of the dunefoot position, which tends to reduce the data variability. Thus, we only analyse shoreline changes with scales ranging from 1 to 20 years.

Two main controlling factors in the shoreline evolution along the Holland coast have been identified: (1) influence of subaqueous bar systems, and (2) changes in the storm-wave conditions reaching the coast. Both factors affect the shoreline evolution of each zone of the coast in a different way. On the other hand, the behaviour of the bar systems is affected by the local shoreface slope.

The longshore rhythmicity of the dunefoot position in Zone II reflects the same scale (2–3 km) as the crescentic morphology of bars. Moreover, the periodicity between successive oscillations in the shoreline is about 10–15 years, which again is similar to the morphological periodicity in bar evolution. The equivalence between both spatial and temporal scales suggests that shoreline and bar disposition and evolution are strongly related, although the cause–effect relationships between these and the precise controlling processes still remain unclarified. Ruessink (1998) suggests that coupling between inner nearshore zone dynamics (and

Table I. Characteristic 'sand waves' recorded on different coastal areas

Reference	Length (km)	Migration rate (m/yr)	Amplitude (m)	Period (yr)
Bruun (1954)	0·5–3	0–1000	60–80	–
Morton (1979)	5–7	–	–	–
	2·5–3	–	–	–
Dolan & Hayden (1981)	> 1	–	–	–
Stewart & Davidson-Arnott (1988)	0·5–2·5	150–300	50–90	10
Verhagen (1989)*	5·5	65	40–60	75–100
Pelczar *et al.* (1990)	5–9	100–200	70–110	50–60
Thevenot & Kraus (1995)	0·75	350	40	–
This study†	2–3	150–200	20	10–15

* Data for the Holland coast
† Based on dunefoot mobility (shoreline should be about twice this value)

probably that of the dunefoot as well) and subaqueous bars could be explained by sediment exchanges across the profile related to the evolutive cycle of bars.

The existence of spatial oscillations in the position of the shoreline, with periodicities that are irregular to quasi-sinusoidal in form, has been known since Bruun (1954). Large-scale (length >1 km) crescentic features along the shoreline are called 'sand waves' by Hom-ma and Sonu (1962) and similar oscillations have been reported on other coasts around the world (Bruun, 1954; Stewart and Davidson-Arnott, 1988; Pelczar *et al.*, 1990; Thevenot and Kraus, 1995). The most frequent spatial scales of these rhythmic features are 2–5 km and their annual rate of migration about 100–300 m (Table I). Along the Holland coast, Verhagen (1989) interpreted the presence of 'sand waves' with a period of 50–150 years and moving towards the north, although no clear explanation of this fact was presented.

The influence of the submerged profile in developing alongshore, quasi-rhythmic patterns has been pointed out in previous studies (Bruun, 1954; Fisher *et al.*, 1984). Processes causing these crescentic features along the shoreline have been related to edge waves (Dolan *et al.*, 1979) or to a non-uniform distribution of energy from refracted waves (Goldsmith, 1976). It can be safely assumed that bar systems act as a filter for the incident wave energy reaching the beach. Along non-uniform, crescentic, bar systems the filtering efficiency of the profile reflects the bar rhythmicity and, consequently, it may partially determine the dune–shoreline evolution along the coast. As a first approximation, it is plausible to assume that the morphological control of the submerged topography on incident wave energy is a dominant factor in developing longshore rhythmic features along the Holland coast. Moreover, the temporal periodicity (about 10–15 years) in the dunefoot oscillations along Zone II appears to be related to the bar behaviour: some disposition of bar systems across the profile (with an apparent return period of 15 years) favours the dissipation of the incident wave energy and the shoreline accretion, whereas when the profile shows other configurations the wave energy reaching the beach is maximum and the shoreline tends to be eroded. The apparent migration towards the south of the accretional and erosional positions of the dunefoot along Zone II (Figure 8) remains unclear. The migration may be related to the oblique disposition of bars with respect to the shoreline or to the existence of alongshore migrations of bar systems and associated rhythmic morphological features.

In Zone II some general displacements of the dunefoot exist that are superimposed on the alongshore oscillations. These beach changes simultaneously affect the entire coast, such as the 'erosional' positions of the shoreline during years 1966, 1975, 1983 and 1990 (Figure 7).

In Zone III, bar systems show a homogeneous disposition and behaviour alongshore. The shoreline evolution is also homogeneous along the coast and no rhythmic patterns are observed. Oscillations in the erosional–accretional positions of the shoreline simultaneously occur along the entire zone and they seem unrelated to the behaviour of bars. On the other hand, most of these general oscillations can be correlated with displacements in Zone II, indicating that the process responsible for these oscillations simultaneously affects the entire Holland coast (Figure 8). This suggests that the external forcing by waves and/or storm surges is the mechanism responsible.

Table II. Normalized cumulative storm-wave parameters during morphological bar cycles in Zone III. The highest energy of the 'surge-storm' parameter takes place during the period 1988–1990, in spite of the fact that the duration of this period is only three years, whereas the other cycles are four years long

Period	'Wave-storm'	'Surge-storm'
1980–83	1·12	1·04
1984–87	1·03	0·90
1988–90	0·84	1·06

The behaviour of the nearshore bars is an important controlling factor in the shoreline evolution along the Holland coast. At present, there is no definitive explanation about what processes produce the morphological bar cyclic behaviour, although the change with depth of the relative importance of bar-degenerating conditions (asymmetric waves) versus the bar-maintaining conditions (breaking waves) has been proposed as a possible mechanism (Wijnberg, 1995). This author points out that 'the exact annual sequence in storm events seems less important for the overall duration of a cycle (of bar evolution) than the fact that a number of varying storm events occurs each year'. The analysis of storm-wave data along the Holland coast seems to confirm this hypothesis. The cyclic bar behaviour in Zone III (in Zone II we do not have enough temporal wave data for the analysis) is not related to the evolution of the wave climate during the study period (individual storm events or yearly cumulative storms). In a prospective way, we took into account the morphological cycle of the outer bar in Zone III (years 1980–1983, 1984–1987 and 1988–1990) (Figure 10). The cumulative storm-wave parameters during these cycles are very similar (Table II), suggesting that the development of a morphological bar cycle needs a certain cumulative amount of energy to be applied and this energy is progressively supplied to the beach by waves during storms. The required wave energy is probably related to the volume of sediment transported during one morphological cycle. From this perspective, differences in the bar behaviour periodicity between Zones II and III can be seen as a consequence of the different size of bars in each zone: larger bars in Zone II require more energy (higher transport of sediment involved) and this energy can only be supplied to the nearshore in a longer period of time.

CONCLUSIONS

A new definition of the dunefoot is introduced for the Holland coast considering both morphological and sediment balance criteria. The defined dunefoot displays a linear correlation with other parameters, such as +1 m NAP, 0 m depth and −1 m depth, during the period 1964–1992. Therefore, we can assume that a cross-shore displacement of the dunefoot will be accompanied by a proportional displacement in the same direction of the other parameters. The dunefoot is less sensitive to low-period changes than other parameters and, consequently, it can be reliably used in the study of the shoreline evolution on a decadal scale.

Processes acting on different temporal scales govern the shoreline evolution along the Holland coast. When short (<one year) and long (>two decades) temporal scales are removed of the analysis, two main controlling processes of the shoreline evolution are identified along this coast: (1) the behaviour of bar systems, and (2) variations in the cumulative annual storm-wave climate affecting the nearshore. The influence of nearshore bars in the shoreline evolution only becomes evident when bar systems are not uniform in a longshore direction. Between km 28 and 54 (Zone II), nearshore bars show crescentic shapes and their morphological evolution (development near the shoreline and offshore migration up to fading away) does not take place simultaneously along the entire zone, which suggests some obliquity of bars with respect to the shoreline. The differential wave energy dissipation on bar systems produces oscillations in the position of the shoreline with the same lengths (2–3 km) as crescentic bar features and the same period (10–15 years) as the morphological bar cycle. When the morphology of nearshore bars is linear and without longshore discontinuities (such as in Zone III) the shoreline behaviour is also homogeneous along the coast and accretional or erosional positions occur simultaneously.

Temporal series of wave height and surge level during storms display seasonal oscillations, but are not clearly related to the observed shoreline evolution. However, the annual cumulative storm parameters defined considering wave height, surge level and storm duration are well correlated to 'erosional–accretional' positions of the shoreline. The cumulative storm effect seems to be the main controlling factor of the dunefoot evolution when the disposition of nearshore bars is homogeneous along the shoreline (Zone III). In areas where nearshore bars show crescentic morphologies (such as north of IJmuiden harbour) the effect of the cumulative storms on the shoreline is superimposed on the differential behaviour of the coast caused by the alongshore disposition of bars. Both processes produce shoreline oscillations of a similar scale (< 20 m).

Cumulative wave parameters seem to be a useful tool in the interpretation of the morphological changes of the littoral zone, in both shoreline and bar evolution. For instance, we have explored the concept that the development of a morphological bar cycle requires a fixed amount of energy that is proportional to the cumulative effect of storm waves and is related to bar position and local shoreface slope. To evaluate the potential application of the concept in the quantitative prediction of shoreline and bar evolution would require the availability of more and longer time series of shore evolution data and a more detailed analysis of the periodicities of storm waves.

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